"On the Conversion of Electric Oscillations into Continuous Currents by means of a Vacuum Valve."   By J. A. FLEMING, M.A., D.Sc., F.R.S., Professor of Electrical Engineering in University College, London.   Received January 24,—Read February 9, 1905.

An electric oscillation being an alternating current of very high frequency, cannot directly affect an ordinary movable coil or movable needle galvanometer.

Appliances generally used for detecting electric waves or electric oscillations are, therefore, in fact, alternating current instruments, and must depend for their action upon some property which is independent of the direction of the current, such as the heating effect or magnetizing force.   The coherer used in Hertzian wave research is not metrical, since the action is merely catastrophic or accidental, and bears no very definite relation to the energy of the oscillation which starts it.   Even the demagnetising action of electric oscillations, though more definite in operation than the contact action at loose joints, is far from being all that is required for quantitative research.   It is obvious it would be an advantage if we could utilise the direct current mirror galvanometer for the detection and measurement of feeble electric oscillations.   This can be done if we can discover a medium with perfect unilateral conductivity.

Some time ago, I considered the use of the aluminium-carbon electrolytic cell with this object.   It is well known that a cell containing a plate of aluminium and carbon, immersed in some electrolyte which yields oxygen, such as dilute sulphuric acid or an aqueous solution of any caustic alkali, or salt yielding oxygen, has a unilateral conductivity within limits.   An electric current under a certain electromotive force can pass through the cell from the carbon to the aluminium, but not in the reverse direction.

This action has been much studied and is the basis of many technical devices, such as the Nodon electric valve.

The electrochemical action by which this unilateral conductivity is produced involves, however, a time element, and after much experimenting I found that it did not operate with high frequency currents. My thoughts then turned to an old observation made by me in 1889, communicated to the Royal Society, amongst other facts, in a Paper in 1889, and also exhibited experimentally at the Royal Institution in 1890.*   This was the discovery : that if a carbon filament electric

* See 'Roy. Soc. Proc.,' vol. 47, p. 122, 1890, "On Electric Discharge between Electrodes at different Temperatures in Air and High Vacua," by J. A. Fleming, communicated December 16, 1889; see also 'Proceedings of the Royal Institution,'

glow lamp contains a pair of carbon filaments or a single filament and a metallic plate sealed into the bulb, the vacuous space between possesses a unilateral conductivity of a particular kind when the carbon filament, or one of the two filaments, is made incandescent. I have quite lately returned to this matter, and have found that this unilateral conductivity exists even with alternating currents of high frequency and is independent of the frequency. Hence, in a suitable form, it seemed possible that such a device would provide us with a means of rectifying electric oscillations and making them measurable on an ordinary galvanometer. The following experiments were, therefore, tried :—

Into a glass bulb, made like an incandescent lamp, are sealed in the ordinary way two carbon filaments, or there may be many filaments. On the other hand, one carbon filament may be used and a platinum wire may be sealed into the bulb terminating in a plate or cylinder of platinum, aluminium or other metal surrounding the filament. It is preferable to use a metal plate carried on a platinum wire sealed into the glass bulb, the plate being bent into a cylinder which surrounds both the legs of the carbon loop. The diagrams in fig. 1 show various forms of the arrangement. Diagram *a* shows a bulb with a single carbon filament surrounded by a metal cylinder, *b* shows one with two carbon filaments, and *c* a carbon filament and two insulated metal plates. The ends of the carbon filament which is rendered incandescent are marked + and − and the terminal of the other electrode of the valve is marked *t*. The bulb must be highly exhausted to about the pressure usual in the case of carbon filament incandescent lamps, and the metal cylinder or plate must be freed from occluded air.

Suppose that we employ such a bulb containing one carbon filament surrounded by a metal cylinder (see *a*, fig. 1). The filament may be of any voltage, but I find it most convenient to employ filaments of such a length and section that they are brought to bright incandescence by an E.M.F. of 12 volts. The voltage and section of the filament should be so arranged that the temperature of the filament corresponds with an "efficiency," as a lamp-maker would say, of 2·75 or 3 watts per candle. The filament is conveniently brought to incandescence by a small insulated battery of secondary cells. A circuit is then completed through the vacuous space in the bulb between the cylinder and the filament by another wire which joins the external terminal *t* of the metal cylinder and that terminal of the carbon filament which is in connection with the negative pole of the heating battery. In this last circuit is placed a sensitive mirror galvanometer of the movable needle or movable coil type, and also a coil which may

be the secondary circuit of an air core transformer in which electric oscillations are set up.   As is now well known, the vacuous space in the bulb permits negative electricity to move in it from the hot filament or cathode through the vacuous space to the cylinder or anode and back through the galvanometer and coil, but not in the reverse direction, as long as the cylinder is cool and the carbon filament not at a temperature much above the melting point of platinum.   To illustrate the action of the bulb as an electrical valve, the following experiments can be shown :—

Electric oscillations are set up in a metal wire circuit by the discharge of a Leyden jar, as usual.   This circuit takes the form of a thick wire of one or more turns, bent into the form of a circle or square. Some distance from this, we place another wire, of several, say eight

Fig. 1.
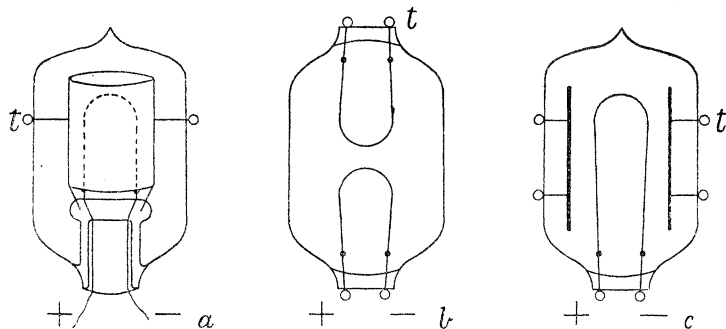
or ten turns, also bent into the form of a circle, and connect this last wire into the circuit of a galvanometer and vacuum bulb made as described, so that it is a circuit having unilateral conductivity.   On exciting the oscillations in the primary circuit by an induction coil we have an alternating high frequency magnetic field produced, which affects the secondary circuit at a distance.   The oscillations in this last are, however, able to flow only in one direction.   Hence, the galvanometer is acted upon by a series of intermittent but unidirectional electromotive forces, and its needle or coil deflects.   Since the field is a high frequency field, we can show the screening effect of a sheet of tin foil or silver paper in a very simple and effective manner by the effect it produces in cutting down the galvanometer deflection when the metal sheet is interposed between the primary secondary circuits.   Also, if we move the secondary coil away from the primary coil or turn the two coils with their planes at right angles to one another, then the galvanometer deflection diminishes or falls to zero because the induction is decreased.   Accordingly, we have in this vacuum valve and

associated mirror galvanometer a means of detecting feeble alternating electric currents or oscillations. Another method is to employ a differential galvanometer and two vacuum valves. These must then be arranged, as shown in fig. 2, one circuit G_1 of the differential galvano-meter is in series with one valve V_1 and the other circuit G_2 with the other valve V_2, but so joined up that currents flowing through the valves in opposite directions pass round the two galvanometer wires in the same direction as regards the needle and, therefore, their effects are added together on the galvanometer needle. Each valve must then have its own separate insulated battery to ignite the filament. Also, it is necessary that the connection with the oscillatory circuit must be made in both cases to the hot filament by that terminal which is in

FIG. 2.
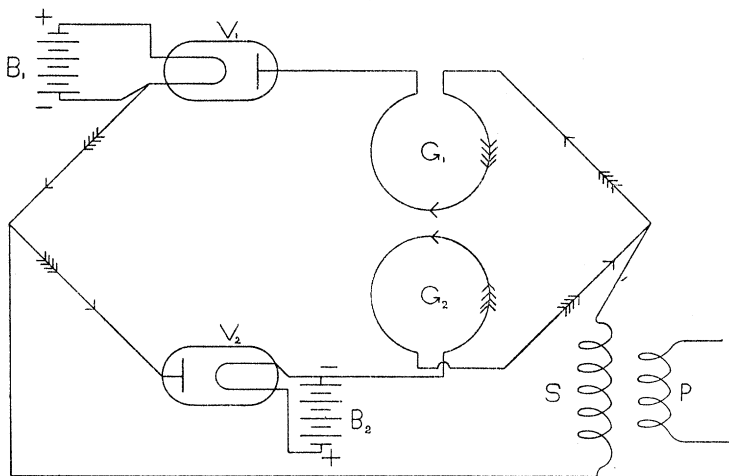
connection with the negative pole of the local battery used to ignite the filament (see fig. 2).

This arrangement of a differential galvanometer and two valves transforms, of course, more of the alternating oscillation into direct current than when one valve alone is used. It provides us with a means of detecting electrical oscillations not merely in closed circuits but in open electrical circuits.

When so using it, it is necessary to associate with the oscillation valve and galvanometer an oscillation transformer for raising the voltage. The resistance of these valves, when in operation, may be anything from a few hundred ohms up to some megohms, depending on the state of incandescence of the filament and upon the electro-motive force employed to drive the current through the vacuous space, as well as upon the size of the filament and the plate. This resistance

does not obey Ohm's law, but the current increases to a maximum and then slightly decreases as the voltage progressively increases. The form of oscillation transformer employed with the device is as follows : A small air-core induction coil has a primary circuit, which consists of 52 turns of gutta-percha covered wire, wound in a helical groove cut on an ebonite rod 0·5 inch in diameter and 6 inches in length. The primary circuit is made of a No. 20 or No. 22 S.W.G. copper wire. The secondary circuit consists of 36,000 turns of fine silk-covered wire, No. 36, wound in six coils, each having about 6000 turns, and all joined in series. This secondary circuit has one terminal connected to one common terminal of the galvanometer and the other to the common terminal of the two oscillation valves (see fig. 4). The primary coil of this oscillation transformer has one terminal connected to earth and the other to a long insulated rod which acts as an aerial or electric wave collector. To prevent the direct action of the transmitter upon the secondary coil by simple electromagnetic induction, it is best to wind the secondary coil in two equal parts in opposite directions and to wind the primary in a corresponding manner.

If an electric wave sent out from a similarly earthed transmitter falls upon the rod, then an electrical oscillation is set up in the receiving circuit and therefore in the primary coil of the oscillation transformer inserted in series with it. This oscillation is raised in voltage by the secondary coil of the transformer, and by reason of the unilateral conductivity of a vacuum valve, placed in series with the coil, one part of the oscillation, viz., the positive or the negative current, passes round the galvanometer coils and affects it.

If we employ a sensitive dead beat galvanometer of the type called by cable engineers a "Speaking Galvanometer," then intelligible signals can be sent by making small and larger deflections of the galvanometer corresponding to the dot and dash of the Morse alphabet ; anyone who can "read mirror" can read off the signals as quickly as they can be sent on an ordinary short submarine cable with this arrangement.

The arrangement, although not as sensitive as a coherer or magnetic detector, is much more simple to use. Also it has one great advantage, viz., that it enables us to examine the behaviour of any particular form of oscillation producer. By means of it we can detect changes in the wave-making power or uniformity of operation of the transmitting arrangement, by the variation of the deflection of the galvanometer. Thus, for instance, if a spark-ball transmitter is being employed and the deflection of the galvanometer in association with the receiving aerial is steady, if we put the slightest touch of oil upon the spark-balls of the transmitter, their wave-making power is increased and the deflection of the galvanometer at once increases. Since the current through the galvanometer is the result of the groups of oscillations

which are created in the receiving circuit, and since in the ordinary transmitter these oscillation groups are separated by wide intervals of silence, it is obvious that we can increase the sensitiveness of the above described arrangement by employing a very rapid break or interruptor with the induction coil. If, for instance, we employ a Wehnelt break with the induction coil or a high speed mercury break or alternating current transformer, we get a far better result as indicated by the deflection of the galvanometer than when employing the ordinary low frequency spring or hammer break.

The point of scientific interest in connection with the device, however, is the question how far such unilateral conductivity as is possessed by the vacuous space is complete. The electrical properties of these vacuum valves have accordingly been studied.

A bulb containing a 12-volt carbon filament rendered brightly incandescent by a current of about 2·7 to 3·7 ampères was employed. The filament was surrounded by an aluminium cylinder. The length of the carbon filament was 4·5 cm., its diameter 0·5 mm., and surface 70 square mm.

The aluminium cylinder had a diameter of 2 cms., a height of 2 cms., and a surface of 12·5 square cms. The filament was shaped like a horse-shoe, the distance between the legs being 5 mm. This filament was rendered incandescent to various degrees by applying to its terminals 8, 9, 10, and 11 volts respectively. Another insulated battery of secondary cells was employed to send a current through the vacuous space from the cylinder to the filament, connection being made with the negative terminal of the latter. The current through the vacuous space and the potential difference of the cylinder and negative end of the hot carbon filament were measured by a potentiometer. The effective resistance of the vacuous space is then taken to be the ratio of the so observed potential difference (valve P.D.) to the current (valve current) through the vacuum.

The following table records the observations. The column headed P.D. gives the potential difference between the hot filament and the cylinder, that headed A gives the current through the vacuous space in milliampères, that headed R the resistance of the space in ohms, and that headed $K10^5$ is 100,000 times the conductivity.

The result is to show that the vacuous space does not possess a constant resistance, but its conductivity increases rapidly up to a maximum and then decreases as the valve potential difference progressively increases. If we plot the current values as ordinates and potential difference of the valve electrodes as abscissæ, we find that the current curve quickly rises to a maximum value and then falls again slightly as the potential difference increases steadily. The conductivity curve also rises to a maximum and then decreases (see fig. 3).

The facts so exhibited are well-known characteristics of gaseous

2 N 2

Table I.—Variation of Current through, and Conductivity of, a Vacuum Valve with varying Electromotive Force, the Electrodes being an Incandescent Carbon Cathode and Cool Aluminium Anode.

Carbon filament at 11 volts, 3·77 amp., 41·47 watts.				Carbon filament at 10 volts, 3·44 amps., 34·43 watts.			
Vacuum Space.				*Vacuum Space.*			
P.D.	A.	R.	K10⁵.	P.D.	A.	R.	K10⁵.
0·6	0·024	25,000	4·0	0·7	0·014	50,000	2·0
5·4	0·264	20,550	4·86	2·8	0·073	38,360	2·6
8·8	0·480	18,330	5·45	8·2	0·392	20,920	4·76
18·2	3·880	4,691	21·4	12·8	0·824	15,530	6·56
22·9	26·790	855	118·1	16·2	1·739	9,316	10·70
29·1	28·02	1,038	96·1	20·1	5·352	3,756	26·6
37·1	28·426	1,305	76·6	23·3	9·68	2,407	41·4
49·0	26·50	1,719	58·0	35·9	10·037	3,577	28·0
70·2	26·87	2,613	38·3	49·7	9·794	5,075	20·0
100·0	24·36	4,105	25·0	71·6	8·920	8,027	12·5
				100·08	8·331	12,010	8·32

Carbon filament at 9 volts, 3·112 amps., 28·0 watts.

Vacuum Space.							
P.D.	A.	R.	K10⁵.	P.D.	A.	R.	K10⁵.
0·5	0·005	100,000	1·0	24·2	2·389	10,130	10·0
2·5	0·049	50,020	2·0	28·2	2·437	11,650	8·6
5·2	0·128	40,625	2·46	36·6	2·508	14,590	6·86
8·3	0·324	25,620	4·0	48·6	2·535	19,170	5·0
8·8	0·361	24,380	4·1	58·5	2·374	24,640	4·0
12·6	0·70	17,970	5·5	72·5	2·253	32,180	3·0
16·4	1·735	9,452	10·5	102·0	2·067	49,350	2·0
20·4	2·351	8,677	11·2				

conduction in rarified gases.* It may be noted that there is in these current-voltage and voltage-conduction curves a general resemblance to the magnetisation and permeability curves of iron.

To examine further the nature of this conduction, the following experiments were made. If a vacuum bulb, as described, is joined up in series with a galvanometer and an electrodynamometer and an alternating electromotive force applied to the circuit, the two instruments will both be affected. The galvanometer is, however, affected only by

* See J. J. Thomson, ' Conduction of Electricity through Gases,' Chap. VIII.

FIG. 3.
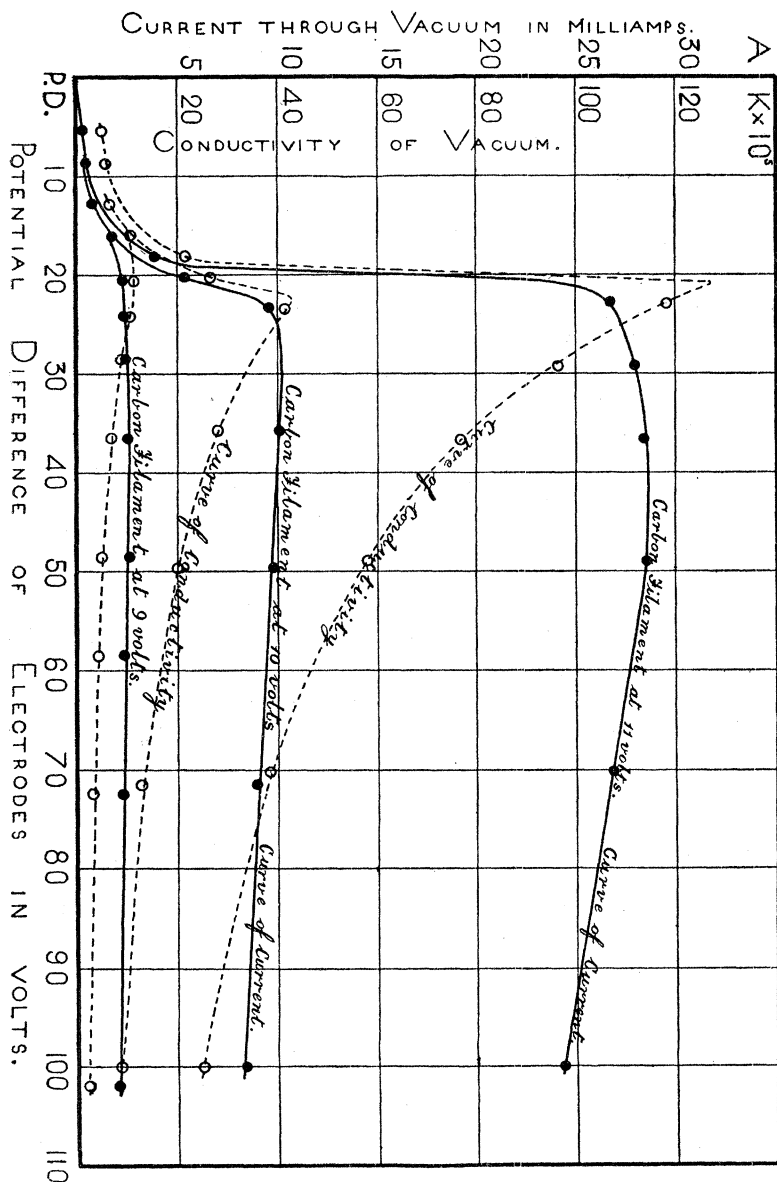
the resultant flux of electricity in one direction. It measures the unidirectional current. The dynamometer is affected by the bilateral flux of electricity and it measures the total or alternating current. If, therefore, the vacuous space is totally non-conducting in one direction,

one half of the alternating current will be cut out. The galvanometer will read the true mean (T.M.) value of the remanent unidirectional current, and the dynamometer will read the root-mean-square (R.M.S.) value. If the conductivity in one direction is not zero, then the galvanometer will read the T.M. value of the difference of the positive and negative currents, but the dynamometer will read the R.M.S. value of their sum.*

In the last case, the current through the valve may be considered to be a continuous current superimposed upon an alternating current.

If we call I the maximum value of the nearly sinoidal current in one direction, and I′ the maximum in the opposite direction, then we may say that the dynamometer reading (D) expressed in true current value is equal to g (I + I′) where g is the *amplitude factor*, and also that the galvanometer reading (G) in true current value is equal to g/f (I − I′) where f is the *form factor* of the current.† Hence—

$$\frac{D}{G} = f\frac{I+I'}{I-I'}, \quad \text{or} \quad \frac{D/G+f}{2f} = \frac{I}{I-I'}.$$

The fraction $\dfrac{2f}{D/G + f}$, say β, expressed as a percentage may be called the *rectifying power* of the valve, for it expresses the percentage which the actual unilateral electric flow or continuous current through the valve is of that continuous current which would flow if the unilateral conductivity were perfect.

Perfect rectifying power, however, does not exist. There is not an infinite resistance to movement of negative electricity from the metal cylinder to the hot filament through the vacuum, although this resistance is immensely greater than that which opposes the movement of negative electricity in the opposite direction. This point was examined, as follows : A very sensitive electrodynamometer was skilfully constructed by my assistant, Mr. G. B. Dyke, the fixed coil having 2000 turns of No. 47 silk-covered copper wire and the movable coil 1000 turns. The suspension of the movable coil was by a fine flat phosphor-bronze wire at top and bottom. The deflection was observed by a mirror and scale.

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* If i is the instantaneous value of a periodically varying current with maximum value I and periodic time T, then the root-mean-square value (R.M.S. value) of i is defined to be $\left(\dfrac{1}{T}\displaystyle\int_0^T i^2 dt\right)^{\frac{1}{2}}$ and the true mean value (T.M. value) of i is defined to be $\dfrac{2}{T}\displaystyle\int_0^{\frac{1}{2}T} i\,dt.$

† The *form factor f* and *amplitude factor g* are the names given by the author (see 'Alternating Current Transformer,' J. A. Fleming, vol. 1, p. 585, 3rd edit.) to the ratio of the R.M.S. to the T.M. value of the ordinates of a single valued periodic curve, and to the ratio of the R.M.S. value of the ordinates to the maximum value during the period.

This dynamometer was placed in series with a shunted movable coil galvanometer of Holden-Pitkin pattern, and the two together placed in series with a variable section of an inductionless coil through which an alternating current was passing. A vacuum valve as above described was in series also with the galvanometer and dynamometer. The alternating current was derived from an alternator giving a nearly true sinoidal electromotive force. The form factor of the electromotive force curve of this alternator was determined and found to be 1·115, that for a true sine curve being 1·111.

The vacuum valve sifted out the alternating current flow and allowed the currents in one direction to pass, but nearly stopped those in the opposite direction. The indications of the electrodynamometer were proportional to the root-mean-square (R.M.S.) value of the sum of the two opposite currents, and that of the galvanometer to the true mean value (T.M.) of their difference. The galvanometer and dynamometer were both calibrated by a potentiometer by means of continuous current, and curves constructed to convert their scale readings to milliampères. Then with various alternating current electromotive forces, their readings were taken when in series with a vacuum valve and recorded in the following tables. The letter D denotes current in milliampères as read by the so calibrated dynamometer and G that read by the galvanometer. The ratio D/G is denoted by α, and the rectifying power, viz., $2f/\alpha + f$ by β.

The table shows that the value of α is not constant, but for each state of incandescence of the filament reaches a maximum which, however, does not greatly differ from the mean value for the range of currents used. If we set out the mean values of β in a curve (see fig. 4), in terms of the power expended in heating the carbon filament, we see that the rectification is less complete in proportion as the temperature of the carbon filament increases. This is probably due to the fact that as the filament gets hotter, it heats the enclosing cylinder to a higher temperature and enables negative electricity to escape from the latter.

Hence, I feel convinced that if the metal cylinder could be kept quite cool by water circulation the rectification would reach 100 per cent. or be complete.

An ideal and perfect rectifier for electric oscillations may, therefore, be found by enclosing a hot carbon filament and a perfectly cold metal anode in a very perfect vacuum. With a bulb such as that used for the above experiments all we can say is that the current passed through the vacuum is from 80 to 90 per cent. continuous, 100 per cent. implying that the vacuum is perfectly non-conducting in one direction and permits the flow of negative electricity only from the hot to the cold electrode. The necessity for keeping the cathode cold is shown by the following experiment :—An alternating-current arc was

Table II.—Ratio of Electrodynamometer (D) to Galvanometer (G) Readings in Milliampères.   Form Factor of E.M.F. Curve = $1 \cdot 115 = f$.

Carbon filament at 11 volts, $3 \cdot 77$ amps., $41 \cdot 7$ watts.

D.	G.	$D/G = a$.	$2f/a + f = \beta$.	
$0 \cdot 85$	$0 \cdot 57$	$1 \cdot 49$	$0 \cdot 86$	
$1 \cdot 33$	$0 \cdot 85$	$1 \cdot 56$	$0 \cdot 83$	
$1 \cdot 87$	$1 \cdot 16$	$1 \cdot 61$	$0 \cdot 82$	
$2 \cdot 30$	$1 \cdot 40$	$1 \cdot 64$	$0 \cdot 81$	Mean
$3 \cdot 20$	$1 \cdot 88$	$1 \cdot 73$	$0 \cdot 78$	$= 0 \cdot 82$.
$3 \cdot 52$	$2 \cdot 10$	$1 \cdot 68$	$0 \cdot 80$	
$4 \cdot 54$	$2 \cdot 81$	$1 \cdot 62$	$0 \cdot 82$	

Carbon filament at 10 volts, $3 \cdot 44$ amps., $34 \cdot 43$ watts.

$0 \cdot 50$	$0 \cdot 34$	$1 \cdot 47$	$0 \cdot 86$	
$1 \cdot 34$	$0 \cdot 86$	$1 \cdot 56$	$0 \cdot 83$	
$2 \cdot 28$	$1 \cdot 48$	$1 \cdot 54$	$0 \cdot 84$	
$2 \cdot 72$	$1 \cdot 68$	$1 \cdot 62$	$0 \cdot 82$	
$2 \cdot 78$	$1 \cdot 71$	$1 \cdot 63$	$0 \cdot 81$	Mean
$3 \cdot 02$	$1 \cdot 87$	$1 \cdot 62$	$0 \cdot 82$	$= 0 \cdot 83$.
$3 \cdot 53$	$2 \cdot 17$	$1 \cdot 63$	$0 \cdot 81$	
$4 \cdot 30$	$2 \cdot 92$	$1 \cdot 47$	$0 \cdot 86$	
$4 \cdot 25$	$2 \cdot 88$	$1 \cdot 48$	$0 \cdot 86$	

Carbon filament at 9 volts, $3 \cdot 112$ amps., $28 \cdot 0$ watts.

$0 \cdot 40$	$0 \cdot 31$	$1 \cdot 29$	$0 \cdot 93$	
$0 \cdot 73$	$0 \cdot 50$	$1 \cdot 46$	$0 \cdot 87$	
$1 \cdot 28$	$0 \cdot 83$	$1 \cdot 54$	$0 \cdot 84$	
$1 \cdot 65$	$1 \cdot 15$	$1 \cdot 43$	$0 \cdot 88$	
$1 \cdot 82$	$1 \cdot 26$	$1 \cdot 44$	$0 \cdot 87$	
$1 \cdot 78$	$1 \cdot 26$	$1 \cdot 41$	$0 \cdot 88$	Mean
$1 \cdot 93$	$1 \cdot 35$	$1 \cdot 43$	$0 \cdot 88$	$= 0 \cdot 89$.
$1 \cdot 94$	$1 \cdot 41$	$1 \cdot 38$	$0 \cdot 89$	
$1 \cdot 87$	$1 \cdot 41$	$1 \cdot 38$	$0 \cdot 91$	
$1 \cdot 83$	$1 \cdot 39$	$1 \cdot 32$	$0 \cdot 92$	
$1 \cdot 73$	$1 \cdot 37$	$1 \cdot 26$	$0 \cdot 94$	

formed between carbon rods, and an iron rod was placed so that its end dipped into the arc.   An ammeter was connected in between either carbon and the iron rod, and indicated a continuous current of negative electricity flowing through the ammeter from the iron rod to the carbon pole.   This current was, however, greatly increased by making the iron rod of a piece of iron pipe closed at the end and

kept cool by a jet of water playing in the interior. In this manner
I have been able to draw off a continuous current of 3 or 4 ampères
from an alternating-current arc using 15 alternating-current ampères.

Returning, then, to the vacuum valve, we may note that the curves
in fig. 3 show that the vacuous space possesses a maximum conduc-
tivity corresponding to a potential difference of about 20 volts between
the electrodes, for the particular valve used. The interpretation of
this fact may, perhaps, be as follows :—In the incandescent carbon
there is a continual production of electrons or negative ions by atomic
dissociation. Corresponding to every temperature there is a certain
electronic tension or percentage of free electrons. If the carbon is

Fig. 4.

Watts expended in Carbon Filament.
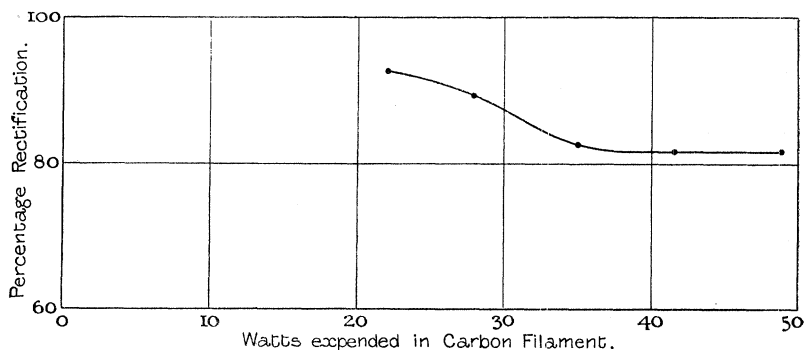
made the negative electrode in a high vacuum these negative ions are
expelled from it, but they cannot be expelled at a greater rate than
they are produced. Therefore, there is a maximum value for the
outgoing current and a maximum value for the ratio of current to
electromotive force, that is for the conductivity.

This fact, therefore, fixes a limit to the utility of the device. The
current through the vacuous space is, to a very large extent, in-
dependent of the electromotive force creating it, and is at no stage
proportional to it, or at least only within a narrow range of electro-
motive force near to the maximum conductivity.

Whilst, therefore, the device is useful as a simple means of detecting
electric oscillations, it has not that uniformity of conductivity which
would make it useful as a strictly metrical device for measuring them.
It can, however, perform the useful service of showing us how far any
device for producing electric oscillations or electric waves produces a
uniform or very irregular train of electric oscillations, and what
changes conduce to an improvement or reduction in the efficiency of
the transmitting device.